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ON THE NECESSITY OF APPLYING A ROTATION TO INSTANTANEOUS VELOCITY MEASUREMENTS IN RIVER FLOWS

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ABSTRACT

In studies on river channel flow turbulence, it is often the case that the measured mean vertical velocity is different from zero, indicating that the frame of reference of the current meter is not parallel to the flow streamline. This situation affects the estimate of Reynolds shear stress in the streamwise and vertical planes and consequently the analysis of the flow turbulent structure. One way to solve this problem is to correct data by applying a rotation and this is reviewed in the first part of the paper. However, in fluvial geomorphology, the studied flow is often complex and streamlines may exhibit significant changes from one point of measurement to the other. In this context, applying a rotation complicates the situation more than it simplifies it. The second part of this paper examines the question of velocity data correction in complex flows using a field example of the turbulent boundary layer over a very rough gravel bed and a laboratory example taken from flow at a river channel confluence. In both cases, velocity vectors are spatially variable. In the first case, errors in the Reynolds shear stress estimates are relatively low (ranging from −13 to 7 per cent/deg) while in the second case, they are much larger (−200 to 164 per cent/deg). The significance of these errors on the interpretation of turbulence statistics in river channel flows is discussed. We propose that corrections should be applied in all clear cases of sensor misalignment and when the frame of reference changes spatially and temporally. However, no corrections should be used where different flow velocity vector orientations, not sensor misalignment, are responsible for the mean vertical velocity differing from zero.

KEY WORDS instantaneous velocity measurements; data correction; fractional error in Reynolds shear stress; complex flows; quadrant analysis; turbulent structure

INTRODUCTION

There is a great deal of ambiguity concerning the necessity to apply a correction to instantaneous flow velocity data in situations where it is believed that the measuring device is misaligned with respect to the local streamline. This question is particularly acute in fields such as geomorphology or sedimentology where the studied flow is often complex and where what is actually measured in a velocity component (either streamwise (u), vertical (v) or spanwise (w)) can be contaminated by other components of velocity. Although this problem is three-dimensional, the most important cases of contamination are from velocity fluctuations in the uv plane since they are responsible for most of the contribution to the Reynolds shear stress and they are used for the detection and characterization of coherent structures in the turbulent boundary layer (Willmarth and Lu, 1972; Lu and Willmarth, 1973; Heathershaw, 1979; Robinson, 1990). The turbulent structures can be described in terms of the frequency and amplitude of 'events' in distinct quadrants defined according to u (streamwise) and v (vertical) velocity fluctuations (Figure 1) (Lu and Willmarth, 1973). These structures are crucial in geophysical flows as they are related to sediment transport dynamics (Jackson, 1976; Leeder, 1983; Best, 1993). However, the links between sediment transport and quadrant analysis rely on the assumption that the frame of reference is parallel to the bed plane and that the mean vertical velocity, normal to the bed, is equal to zero; hence, positive v indicates a motion away from the bed and is related to sediment suspension (Leeder, 1983;

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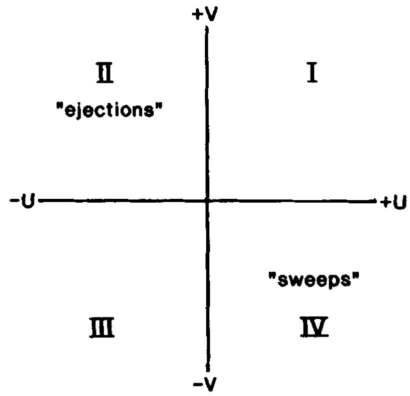

Figure 1. Quadrant plot of streamwise (u) and vertical (v) turbulent flow components

Lapointe, 1992) while negative v is associated with bed load transport as it indicates a motion of fluid towards the bed (Grass, 1983; Williams *et al.*, 1989; Best, 1992).

When the mean vertical velocity, $<v>$, differs from zero, several authors choose to correct data by applying a rotation, assuming that the frame of reference is tilted with respect to the mean streamline because of a misalignment of the sensor (Heathershaw, 1979; Soulsby, 1980; West and Oduyemi, 1989; Lapointe, 1992; Kostachuk and Church, 1993). This assumption, however, may be misleading as $<v>$ can differ from zero because the streamlines are at an angle with the horizontal even if the sensor is well aligned with respect to a general frame of reference for all the measurements. This is the case where secondary flows induced by bends or channel cross-sectional geometry are significant, at the entrance of a pool or in a scour zone, for example, or on the stoss side of a dune. It is also the case in atmospheric boundary layers with flow over hills (Kaimal and Finnigan, 1994). These types of correction and their effect on the Reynolds shear stress will be reviewed in the first part of the paper. We will also attempt to clear up some of the confusion surrounding this question, which arises from the fact that published equations on the fractional error in Reynolds shear stress are not always presented in the same way.

In many studies, however, such a correction is not used systematically, even in cases where $<v>$ is likely to be truly different from zero (Etheridge and Kemp, 1978; Clifford and French, 1993, Nelson *et al.*, 1993). The omission to correct data in these cases may be deliberate but the authors do not give any indication whether it was considered or not. Since angles of deviation are not given, it becomes impossible to evaluate the error in the estimation of Reynolds shear stress in these cases. In the second part of the paper, we will examine more closely the implications of the application (or the non-application) of a correction to velocity measurements in environments relevant to Earth scientists, especially geomorphologists. Complex flows where streamline angles are highly deviant from the horizontal are considered to show the effects of not correcting the velocity measurements on the Reynolds shear stresses. This problem will be illustrated using a field and a laboratory example. Finally, we will offer suggestions on the question of whether or not a correction should be applied to data for different situations often encountered in fluvial geomorphology.

FRACTIONAL ERROR IN REYNOLDS SHEAR STRESS

Several studies have examined the effects of a misalignment of the sensor or a buoy motion on the measurement of Reynolds shear stress, hereafter denoted RS (Deacon, 1968; Kraus, 1968; Pond, 1968; Kaimal and Haugen, 1969; Heathershaw, 1979). In order to evaluate these effects, values for u and v components were computed for a hypothetical rotation of the data with the following equations (Pond, 1968):

$$u_t = u_s \cos\phi + v_s \sin\phi \tag{1}$$

$$v_t = -u_s \sin\phi + v_s \cos\phi \tag{2}$$

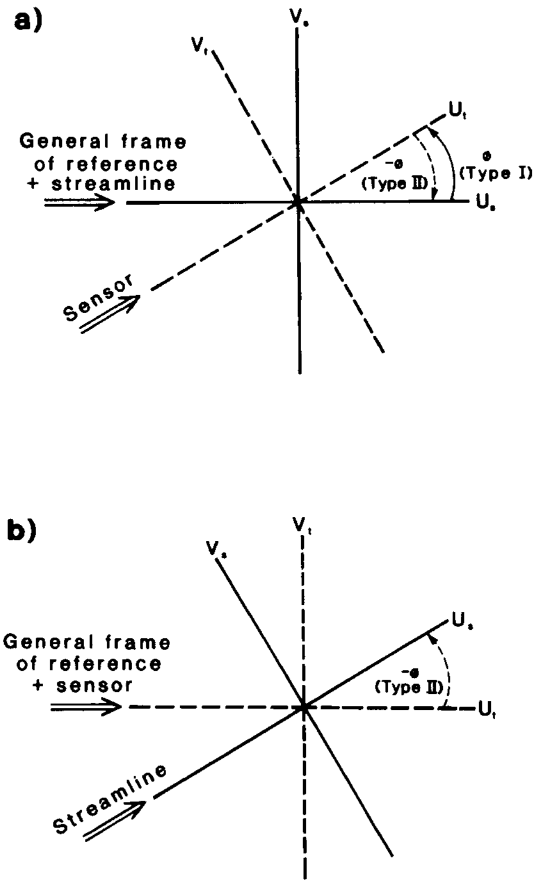

Figure 2. Illustration of the two types of rotation (Types I and II, related to Equations 1 and 2) for (a) sensor misalignment and (b) local streamline at an angle with respect to the mean streamline. Dashed lines and solid lines represent the orientation of the sensor and of the streamline, respectively

where u and v are streamwise and vertical velocity fluctuations, the subscripts t and s refer respectively to the tilted and to the flow streamline velocity fluctuations, and ϕ is the angle of the rotation. Note that Equations 1 and 2 are used to compute tilted data (u_t, v_t) using well aligned data (u_s, v_s) in order to estimate the theoretical fractional error in RS that would result from such a rotation. In other words, the motion is *from* a frame of reference parallel to the mean streamline ($<v>= 0$) *to* one that is tilted by an angle ϕ ($<v>\neq 0$) due to misalignment of the sensor. This is designated here as a Type I rotation (Figure 2a).

However, these equations can also be used to correct data in the case where the sensor is misaligned, i.e. the measured $<v>$ is different from zero. Indeed, in field deployments, there can be great difficulty aligning the probes of current meters such that the u component is perfectly parallel to the flow streamline at each measuring point. In most cases, it is assumed that streamlines are parallel to the bed plane, which is roughly horizontal for a short river reach. Therefore, the simplest way of choosing a frame of reference for a flow sensor is to position it with respect to the bed (or the horizontal), not to the streamline. If a misalignment of the sensor occurs, part of the measured instantaneous vertical velocity component will be contaminated by the measured streamwise component, thus increasing their cross-correlation. This results in corrupted RS times series as well as mean RS estimates (Kaimal and Haugen, 1969; Lapointe 1992). The rotation of data in these cases in order to bring $<v>$ back to zero is *from* a tilted position *to* the streamline orientation that conforms to a frame of reference (generally assumed to be parallel to the bed) (Kaimal and Haugen, 1969; West and Oduyemi, 1989; Lapointe, 1992). This corresponds to a Type II rotation where $\phi = -\phi$ in Equations 1 and 2 (Figure 2).

Note that the term 'misalignment' can generate some confusion as it is used to described indiscriminately

any situation where $<v>$ is different from zero. This will indeed occur when the sensor is tilted with respect to the general frame of reference in the case where the streamline is actually parallel to the bed (Figure 2a). However, $<v>$ may differ from zero, even if the sensor is parallel to the general frame of reference (the horizontal plane), if the streamline is at an angle with respect to the horizontal plane (Figure 2b). Although both situations can be corrected using the same Equations (1 and 2), there is a conceptual difference between them. The first type of error (Figure 2a) is clearly geometrical and truly corresponds to a sensor misalignment. However, the second type of error (Figure 2b) is due to a streamline deviation from the frame of reference used to measure velocity. In this case, the assumption that streamlines are parallel to the bed plane is not valid for the studied environment.

Based on Equations 1 and 2, Pond (1968) derived the tilted value of RS, equal to:

$$<u_t v_t> = <u_s v_s> \cos 2\phi + \frac{\sin 2\phi}{2}(<v_s^2> - <u_s^2>) \tag{3}$$

(Note: for simplicity, we denote the RS with $<uv>$ rather than $-\rho <uv>$, where ρ is water density, as this does not affect the fractional error estimate.) From Equation 3, the fractional error in RS is determined as follows:

$$\text{fractional error } = \frac{<u_t v_t> - <u_s v_s>}{<u_s v_s>} = \cos 2\phi - 1 + \frac{\sin 2\phi}{2<u_s v_s>}(<v_s^2> - u_s^2>) \tag{4}$$

which, when presented differently (Kaimal and Haugen, 1969), becomes:

$$\text{fractional error } = \cos 2\phi - 1 + \frac{\sin 2\phi}{2r_{\text{usvs}}}\left(\frac{1}{\alpha} - \alpha\right) \tag{5}$$

where r_{usvs} is the cross-correlation coefficient between u_s and v_s and $\alpha = \sigma_{\text{us}}/\sigma_{\text{vs}}$, the ratio of u_s and v_s standard deviations. Note that for small angles, $\cos(2\phi) - 1 \approx 0$ and for a Type I rotation Equation 5 simplifies to:

$$\text{fractional error } = \frac{\sin 2\phi}{2r_{\text{usvs}}}\left(\frac{1}{\alpha} - \alpha\right) \tag{6a}$$

and for a rotation of Type II to:

$$\text{fractional error } = \frac{\sin 2\phi}{2r_{\text{usvs}}}\left(\alpha - \frac{1}{\alpha}\right) \tag{6b}$$

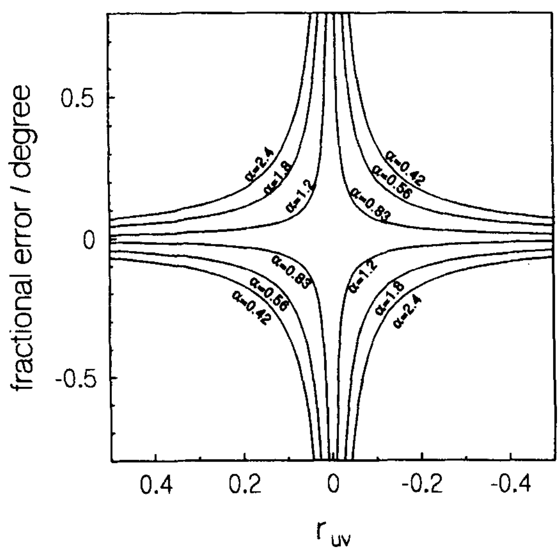

Figure 3. Fractional error per degree as a function of r_{uv} for different values of α (computed with Equation 6)

Thus, the fractional error per degree is dependent solely on the cross-correlation coefficient and the ratio of standard deviations, the latter usually being greater than one in a typical turbulent boundary layer. This relation is illustrated in Figure 3. As the cross-correlation coefficient reaches strong (negative or positive) values, the fractional error decreases markedly and the effect of α becomes negligible. However, as the cross-correlation gets closer to zero, the fractional error per degree becomes important, particularly when α is significantly different from one. Similarly, Figure 3 shows the significant effect of increasing α on the fractional error for different cross-correlation coefficients. Using these graphs, it is possible to estimate the effects of misalignment in environments which are well documented in terms of r_{uv} and α. However, Figure 3 illustrates the difficulty one encounters when attempting to determine an average RS fractional error per degree irrespective of the environment. A statement giving only an average fractional error is uninterpretable unless r_{uv} and α are known. This may explain the somewhat large discrepancies observed in the literature where the reported average fractional errors per degree vary from 5–10 per cent (Pond, 1968), 8·5 per cent (Deacon, 1968), 9–15 per cent (Kraus, 1968), 13 per cent (Pond *et al.*, 1971) to 8–59 per cent (Heathershaw, 1979). However, in a typical boundary layer where $r_{uv} = -0{\cdot}4$ (McQuivey, 1973) and $\alpha = 1{\cdot}4$ (Townsend, 1976), the fractional error is small (3 per cent/deg) and the omission to correct data would not greatly affect the RS.

COMPLEX FLOWS

In fluvial geomorphology, instantaneous velocities are often measured in complex flows. For instance, measurements of flow over bedforms (Lapointe, 1992), in a riffle–pool sequence (Clifford and French, 1993), over a gravelly bed where vortex shedding over clasts is present (Robert *et al.*, 1992) or at a river channel confluence (Biron *et al.*, 1993) will often exhibit mean vertical velocities significantly different from zero. The problem in these complex flows is entirely different from the sensor misalignment problem where the streamlines are assumed to be parallel to each other, i.e. where the deviation is identical for all points and corresponds to the angle of tilt of the sensor. In this case a correction is required even if, as was shown with Figure 3, the error might not be important for a simple turbulent boundary layer. In complex flows, however, the mean vectors for each measuring point may vary markedly. For example, flow on the crest of a dune has a motion towards the water surface but, in the separation zone downstream from the crest, mean vectors are oriented towards the bed (Nelson *et al.*, 1993). To further complicate the situation in complex flows, there may also be a compounding effect due to the misalignment of the sensors.

Applying a correction using Equations 1 and 2 in complex flows, where the mean vector orientation is spatially variable, would result in adjusting the frame of reference from point to point since the angle ϕ varies locally. This greatly complicates, if not hinders, the interpretation of results. Also, according to Wyngaard (1981), Equations 1 and 2 are only valid in a flow where the streamlines are parallel. On the other hand, not correcting data in these cases creates a situation where, if $<v>$ is positive, events may be located in quadrants III and IV ($v < 0$) even if they have a positive vertical velocity. Accordingly, quadrants I and II ($v > 0$) may include fluctuations oriented towards the bed, in the case where $<v>$ is negative. The interpretation of coherent structures from the quadrants is complicated by this contamination as residence times within each quadrant and average periodicities of the coherent structures (e.g. ejections or sweeps) will be biased. Furthermore, the links with sediment transport become dubious as motion towards the bed, capable of entraining sediments, is no longer limited to quadrants III and IV. The opposite is true for motion towards the surface associated with sediment suspension which will occur in quadrants other than I and II.

The problem of data correction in complex flows will be examined in more detail using two examples: (1) field deployment with electromagnetic current meters (ECMs) where data were collected in a gravel-bed river, and (2) a laboratory study with a model of confluence where a laser Doppler anemometer (LDA) was used to measure velocity fluctuations.

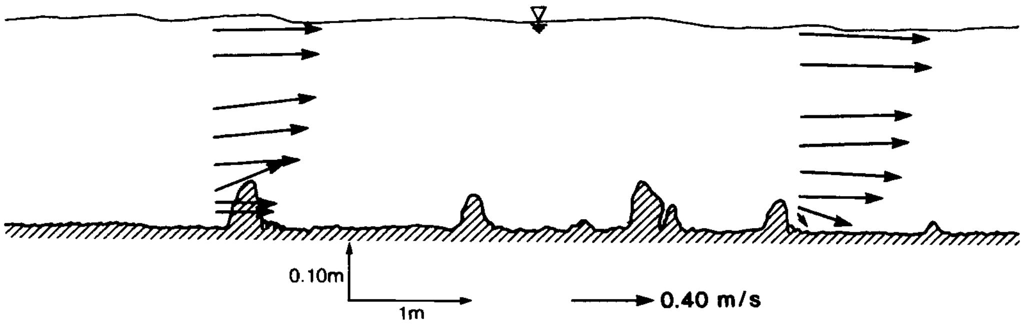

Figure 4. Vectors in the uv plane above a gravel-bed river (Eaton River)

Example 1: gravel-bed river

Velocity profiles were collected in a gravel-bed river (Eaton North River, Québec, $D_{84} = 52$ mm) using an array of four Marsh McBirney ECMs (three 523 models, diameter 13 mm, and one 512 model, diameter 38 mm) with a time constant of 0·05 s. Data were collected at a sampling frequency of 20 Hz during 1 min. The four ECMs were mounted on the same rod and care was taken to align them so the u electrodes were parallel to the bed and parallel to each other. The array was used at two vertical positions in the flow, resulting in eight point velocity profiles. Figure 4 shows the velocity vectors at these eight vertical positions at two longitudinal positions. According to Robert *et al.* (1992), the presence of large clasts on the bed gave rise to vortex shedding and flow separation in the lee of the obstacles, resulting in mean vertical velocities different from zero close to the bed. Note that the angle of the vectors greatly changes from one point to the other and that it is close to 0° higher in the water column. This indicates that misalignment of the sensors due to an inclination of the wading rod cannot be the sole cause of $<v>$ being different from zero. Table I summarizes the main characteristics of the flow for the 16 measuring points examined here. The RS fractional error per degree in this example varies from -13 to $+7$ per cent, which is in good agreement with previous observations (Kraus, 1968; Heathershaw, 1979). The standard deviation ratio (α) varies from 0·8 to 2·0. Using the minimal and

Table I. Characteristics of the velocity data samples

	Min.	Max.	Number of cases < 0	Number of cases ≥ 0	Mean < 0	Mean ≥ 0	Std < 0	Std ≥ 0
Case 1: gravel-bed river								
α	0·8	2·0	n.a.	16	n.a.	1·3	n.a.	0·4
r_{uv}	−0·43	0·12	15	1	−0·22	0·12	0·09	–
ϕ (deg.)	−48	21	10	6	−7·9	6·5	14·9	7·1
Fractional error	−1·5	2·3	6	10	−0·31	0·43	0·60	0·73
Fractional error/degree	−0·13	0·07	11	5	−0·05	0·02	0·04	0·03
Case 2: laboratory confluence								
α	0·7	2·5	n.a.	82	n.a.	1·4	n.a.	0·3
r_{uv}	−0·46	0·50	59	23	−0·18	0·11	0·13	0·11
ϕ (deg.)	−25	52	63	19	−6·6	14·7	6·0	17·0
Fractional error	−11·9	22·6	40	42	−1·37	1·70	2·63	4·76
Fractional error/degree	−2·00	1·64	57	25	−0·13	0·29	0·28	0·44

Note: The statistics (means and standard deviations) are given for the negative (< 0) and positive (≥ 0) cases separately. If all cases were used to compute the means, the values obtained would be close to zero; n.a. indicates cases where there cannot be any negative values

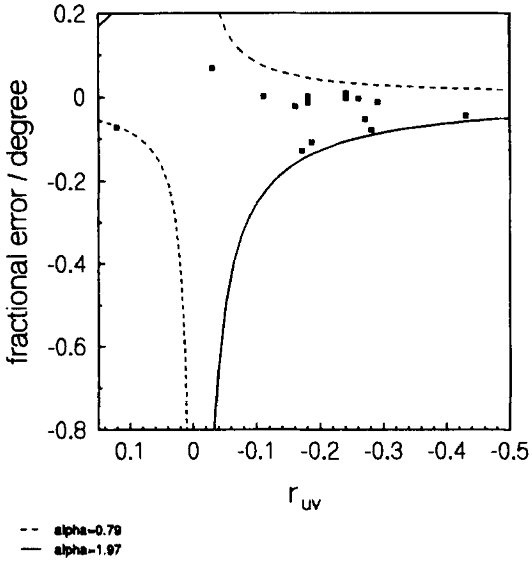

Figure 5. Fractional error per degree (fractional error/($\phi = \tan^{-1}(<v> / <u>)$) as a function of r with theoretical limits based on the minimum and maximum α in the gravel-bed river example and computed using Equation 6

maximal values of α it is possible to determine the limits of the fractional error per degree for different cross-correlation coefficients (Figure 5). It can be seen that in most cases the fractional error per degree is not very large, mainly because the absolute value of cross-correlation is high ($r_{uv} < -0{\cdot}15$ for all but three cases).

Example 2: confluence model

A confluence model was placed into a recirculating flume in order to examine the complex flow turbulence generated at these sites when the tributary bed is higher than that of the main channel (Figure 6). The tributary ended at a 90° step, 0·03 m high, and the presence of a separation zone in the lee of the step combined with the turbulence in the mixing layer between the two flows generated a complex flow field (Biron *et al.*, in press). Velocity was measured at 82 points at 0·03 m above the bed (see Figure 6) with a Dantec

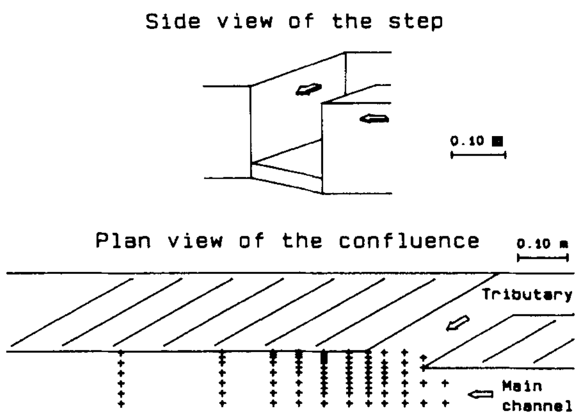

Figure 6. Sketch of the laboratory confluence with the location of the 82 measuring points. Note the presence of a 90° step (0·03 m high) in the tributary channel

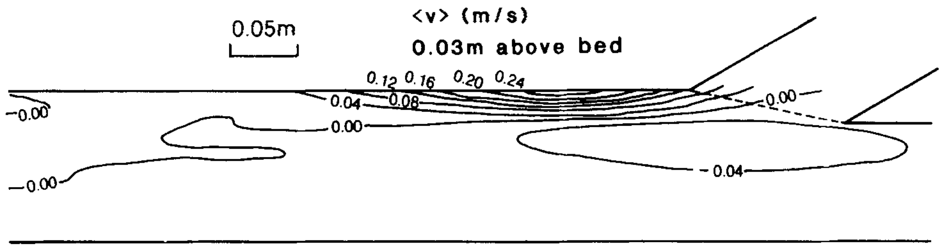

Figure 7. Spatial pattern of $<v>$ at the confluence (0·03 m above bed)

two-component LDA operated in the backscatter mode at an average sampling frequency of 300 Hz, and later subsampled at 40 Hz. Sensor misalignment is completely excluded since the laser beams were perfectly parallel and normal to the bed plane (a smooth perspex floor) for the u and v component, respectively. The presence of a tributary step gave rise to strong negative vertical velocity downstream of the step while an upwelling motion in the downstream junction corner shifted the local streamlines towards the water surface (Figure 7). The angles of deviation varied from −25° to 52° (Table I). In Table I, it can clearly be seen that the fractional error per degree is much higher than it was in the previous example and hence much higher than any estimate given in the literature. This is partly due to a higher α value (an average of 1·4 compared to 1·3 in the gravel-bed river) and, more importantly, to values of r_{uv} closer to zero. The range of values for r_{uv} is much larger for this case than in the gravel-bed case (compare standard deviations of r_{uv} for both examples in Table I). Note as well the presence of positive cross-correlation at 23 measuring points. Figure 8 shows the spatial distribution downstream of the confluence of the RS computed from original and corrected data. Although the general pattern is preserved after the correction is applied, it can be seen that the zones where $<v>$ is significantly different from zero (Figure 7), particularly the downstream junction corner, are greatly modified. These zones correspond to the local maxima in the fractional error spatial

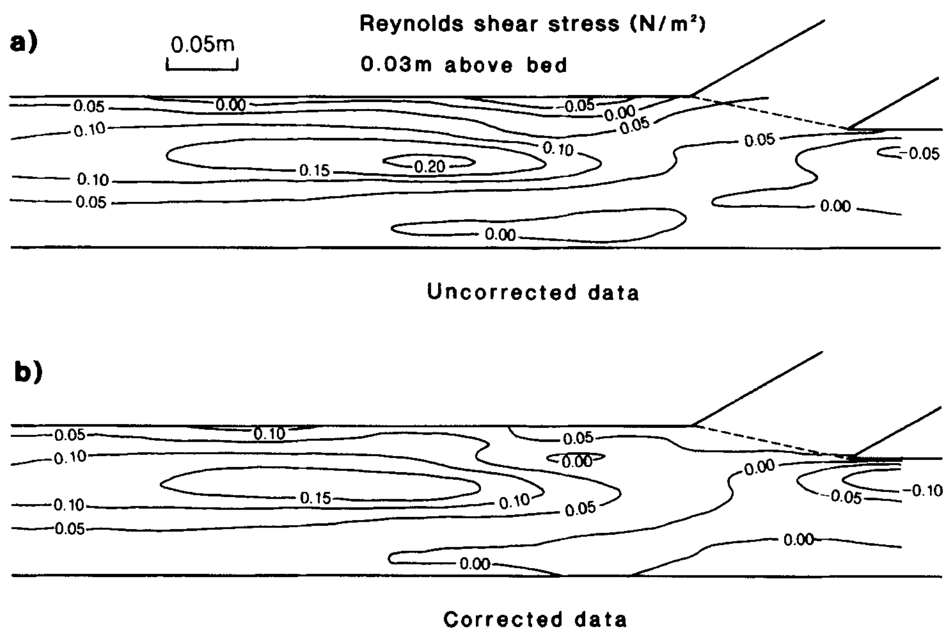

Figure 8. Spatial pattern of the Reynolds shear stress ($-\rho <uv>$) at the confluence (0·03 m above the bed) estimated from (a) raw data and (b) corrected data

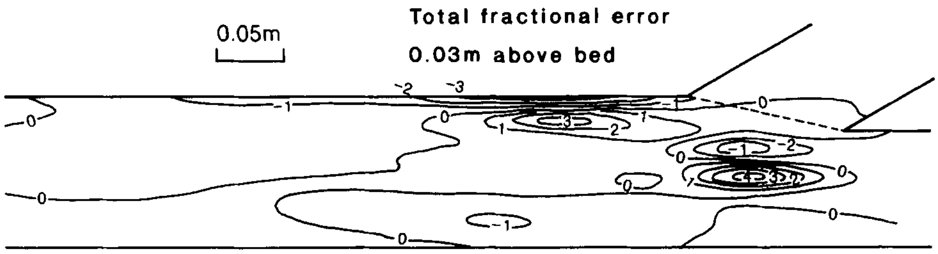

Figure 9. The spatial distribution of the fractional error in Reynolds shear stress (computed with Equation 5) at the confluence (0·03 m above the bed)

distribution. As shown in Figure 9, these maxima can be as large as 400 per cent, which is an enormous error.

DISCUSSION

In both examples, the local streamline varied markedly from one point of measurement to the other but the measurement frame of reference was identical for all points. At present, we are not aware of any reference prescribing whether corrections should be applied in such cases. In these complex flows, we believe that rotating the axes would complicate the analysis more than anything else. For instance, what does a quadrant IV event indicate if the frame of reference adjusted to the streamline is at a 45° angle with the bed? How would these turbulent motions act with the bed sediments? We do not have an ideal solution to this problem and we can only state what appears to us as the more sensible procedure. Whenever $<v>$ with respect to $<u>$ differs markedly from one point to the other, Equations 4 or 5 (valid for any angle of deviation) should be used to estimate the error associated with the computation of RS and the computed error should be taken into account in the interpretation of the results. But the quadrant analysis should be performed on raw data, i.e. with an identical frame of reference for each measuring point. However, the analysis must take into account the fact that the points more likely to flip-flop from one quadrant to the other due to the *uv* vector angle are those of lowest RS. Therefore, restricting the interpretation to strong events can attenuate this problem.

However, it must be stressed that this solution is only valid if misalignment of the sensor can confidently be excluded as a cause of vector deviation. If this is not the case, two distinct situations may occur. First, there can be a constant misalignment through space and time which can be detected by looking at vectors which would normally be parallel to the bed (e.g. the topmost part of the boundary layer). The correction should then be applied using a constant ϕ equal to the estimated angle of deviation due to the sensor but regardless of the local deviations in the vector angle due to flow complexity (i.e. not equal to $\tan^{-1}(<v>/<u>)$ of each measuring point). The second situation concerns more specifically field data where it is often impossible to see how the sensor is deployed near the bed. In these conditions, the current meter set-up can be lying on the bed with varying topography in both space and time (e.g. dunes migrating past the measurement point). The frame of reference is no longer identical from one point to the other as, for example, the sensor might be aligned with a dune stoss side at one moment and with the lee side at another. Therefore, the correction should be applied using $\phi = \tan^{-1}(<v>/<u>)$. This can, however, create difficulties in analysing the spatial pattern of RS and the fractional error should be estimated at each point and considered in the interpretation of the results as done, for example, by Heathershaw (1979).

CONCLUSIONS

One key element to consider in making decisions on data correction is the necessity to facilitate as much as possible the comparison between data. It is somewhat ironic to realize that the cases where the application of

a correction is the most straightforward – in simple turbulent boundary layers where streamlines are assumed to be parallel to the bed – are also the cases where the fractional error would be less important because of the combined effects of a strong cross-correlation coefficient and an α value close to 1·4. However, in complex flows where $<v>$ varies markedly in space, we make the following suggestions.

1. Corrections should be applied in all clear cases of sensor misalignment, i.e. a constant shift in the velocity vector where ϕ in Equations 1 and 2 is constant for all measuring points;
2. Corrections should also be applied when the frame of reference is changing spatially or temporally, as can occur in field deployments where sensors lie above a bedform field. In that case, ϕ is equal to $\tan^{-1}$ $(<v> / <u>)$ and is therefore not constant from one point to the other. In the case of temporal changes, the stationariness of $\tan^{-1}$ $(<v> / <u>)$ should be tested and the time series truncated in order to obtain constant ϕ segments.
3. Corrections should not be used where flow velocity vector orientation, not sensor misalignment, is responsible for $<v>$ being markedly different from zero. However, estimates of the fractional error in RS should be given in these cases and should be taken into account in the comparative analysis of the obtained values.

These suggestions will hopefully clarify the situation prevailing at the moment where there is a lack of consensus on that matter. It is important to insist that, whether or not a correction is applied to instantaneous velocity measurements, the data processing procedure be clearly stated in all future publications on flow turbulence in river channels. This will ensure that turbulence statistics can be compared and interpreted in the best light.

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